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DURABILITY METHODS DEVELOPMENT
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DURABILITY ANALYSIS: STATE-OF-THE-ART ASSESSMENT

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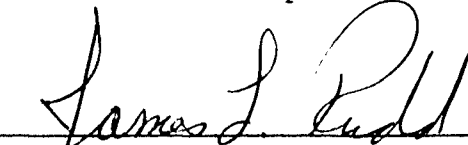
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A critical evaluation of three analytical approaches is made to determine their applicability and/or potential for analytically assuring airframe durability during the design stage. A suitable analytical format for quantifying durability damage is developed based on U. S. Air Force durability design specifications and durability analysis needs. Air Force durability requirements are briefly reviewed and discussed. Three potential approaches (continued)		

20. for durability damage analysis are conceptually evaluated and discussed: (1) Conventional Fatigue Analysis (Palmgren-Miner Rule), (2) Deterministic Crack Growth Approach, and (3) Probabilistic Crack Growth Approach. The resulting evaluation provides the prerequisite work needed to develop a durability analysis methodology. The probabilistic crack growth approach is found to be the most promising for developing the durability analysis methodology under Phase I.

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FOREWORD

This program is conducted by General Dynamics, Fort Worth Division with George Washington University (Dr. J. N. Yang) and Modern Analysis Incorporated (Dr. M. Shinozuka) as associate investigators. This program is being conducted in three phases with a total duration of 50 months.

This report was prepared under Air Force Contract F33615-77-C-3123, "Durability Methods Development". The program is sponsored by the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, with James L. Rudd as the Air Force Project Engineer, Dr. B. G. W. Yee of General Dynamics' Materials Research Laboratory as the Program Manager and Dr. S. D. Manning as the Principal Investigator. This is Phase I of a three phase program.

This report (Volume II) documents the initial ground-work required to develop the durability damage analysis methodology (Volume I and V) under Phase I. Other Phase I reports are:

Volume I - Phase I Summary

Volume III - Structural Durability Survey:
State-of-the-Art Assessment

Volume IV - Initial Quality Representation

Volume V - Durability Analysis Methodology Development

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S E C T I O N I

INTRODUCTION

The U. S. Air Force has structural integrity requirements (i.e., strength, rigidity, durability and damage tolerance) for assuring aircraft operational readiness [1]. This report is concerned with the durability portion of structural integrity [1-3]. Specifically, it is concerned with the analytical assurance of airframe durability during the design stage - before the airframe is committed to verification testing [3] or service.

Durability is defined as: "the ability of the airframe to resist cracking (including stress corrosion and hydrogen induced cracking), corrosion, thermal degradation, delamination, wear, and the effects of foreign object damage for a specified period of time" [1]. An airframe must be durable to minimize structural maintenance problems and functional problems (e.g., fuel leakage, loss of control effectiveness or loss of cabin pressure) affecting aircraft operational readiness and user life-cycle-costs [2].

Detailed Air Force analytical and experimental durability design requirements are presented in Military Specifications MIL-A-008866B [2] and MIL-A-008867B [3], respectively. MIL-A-008866B requires that the airframe be designed to have an "economic life" greater than the design service life when subjected to the design service loads/environments spectra [2]. Economic life must be analytically quantified at the design level [2] and then be experimentally verified [3].

Current definitions of economic life are vague. Two proposed definitions are: (1) "...the occurrence of widespread damage which is uneconomical to repair and, if not repaired, could cause functional problems affecting operational readiness. This can generally be characterized by a rapid increase in the number of damage locations or repair costs as a function of cyclic test time" [1], and (2) "...that point in time when it is more economical to replace the structure than it is to continue to repair it" [4]. While clear in intent, these definitions do not provide a

sharply defined criterion for contractual compliance with the Air Force' durability requirements. Currently, the economic life of an airframe is subjectively defined based on the results of the durability test article and tear down inspection. A quantitative definition of economic life does not currently exist.

The Air Force' durability requirements need to be refined, and new durability analysis methodology for implementing these requirements developed. A quantitative definition of economic life is needed to serve as a standard for analytical assurance of airframe durability and for experimental verification. Such a standard depends on the Air Force' definition of: (1) widespread damage, (2) acceptable limits for structural maintenance costs before replacement, and (3) intolerable maintenance limits for operational readiness. Analytical tools are needed for quantifying durability damage so that durability design tradeoffs and Air Force options affecting airframe economic life and operational readiness can be evaluated during the design stage. Criteria are needed for determining if parts are critical for durability or damage tolerance [5]. Also criteria and guidelines are needed for quantifying economic life.

A three phase program was initiated by the Air Force in 1978 [6]. Two objectives of this program are: (1) develop and verify an analytical methodology for quantifying durability damage for airframes at the design level and (2) develop a durability design handbook with procedures and guidelines for implementing the Air Force' durability requirements.

The objectives of this report are: (1) define the analytical format best suited for quantifying durability damage and (2) critically evaluate the applicability and potential of three different analytical approaches for quantifying durability damage. Results from this report will provide the basis for developing the durability analysis methodology under Phase I of the program.

Objectives of this report will be satisfied as follows. Durability damage analysis requirements will be discussed in terms of the Air Force' durability requirements and a suitable analytical format for quantifying durability damage will be discussed.

Three analytical approaches will be conceptually described, compared and discussed in terms of the required analytical format for quantifying durability damage: (1) Conventional Fatigue Analysis (CFA), (2) Deterministic Crack Growth Approach (DCGA) and (3) Probabilistic Crack Growth Approach (PCGA). Finally, the applicability and usefulness of the three approaches for quantifying durability damage will be assessed.

S E C T I O N I I

DURABILITY DAMAGE ANALYSIS FORMAT DEVELOPMENT

2.1 INTRODUCTION

An analytical format for quantifying durability damage for an airframe and its components is described herein. This format is based on the following considerations: (1) durability design requirements [1-3], (2) durability analysis issues, (3) durability damage analysis objectives, and (4) analytical format for durability damage analysis.

2.2 DURABILITY DESIGN REQUIREMENTS

The objective of the Air Force' durability design requirements for aircraft structures is to minimize in-service maintenance costs and maximize operational readiness through proper selection of materials, stress levels, design details, inspections, and protective systems. Durability structural integrity requirements are given in MIL-STD-1530A [1], detailed durability design and analytical requirements in MIL-A-008866B [2], and durability verification test requirements in MIL-A-008867B [3].

2.2.1 Analytical Requirements

Analyses are required to demonstrate that the "economic life" of the airframe is greater than the design service life when subjected to the design service loads and design chemical/thermal environment [1,2]. This requirement is conceptually described in Fig. 1 in terms of the cracking durability damage mode. Economic life can generally be characterized by a rapid increase in the number of damage locations or repair costs as a function of time [2] (Fig. 2).

MIL-A-008866B [2] states the analytical requirements as follows: "...The approach shall account for those factors affecting the time for cracks or other damage to reach sizes large enough to necessitate the repair, modification, or replacement of

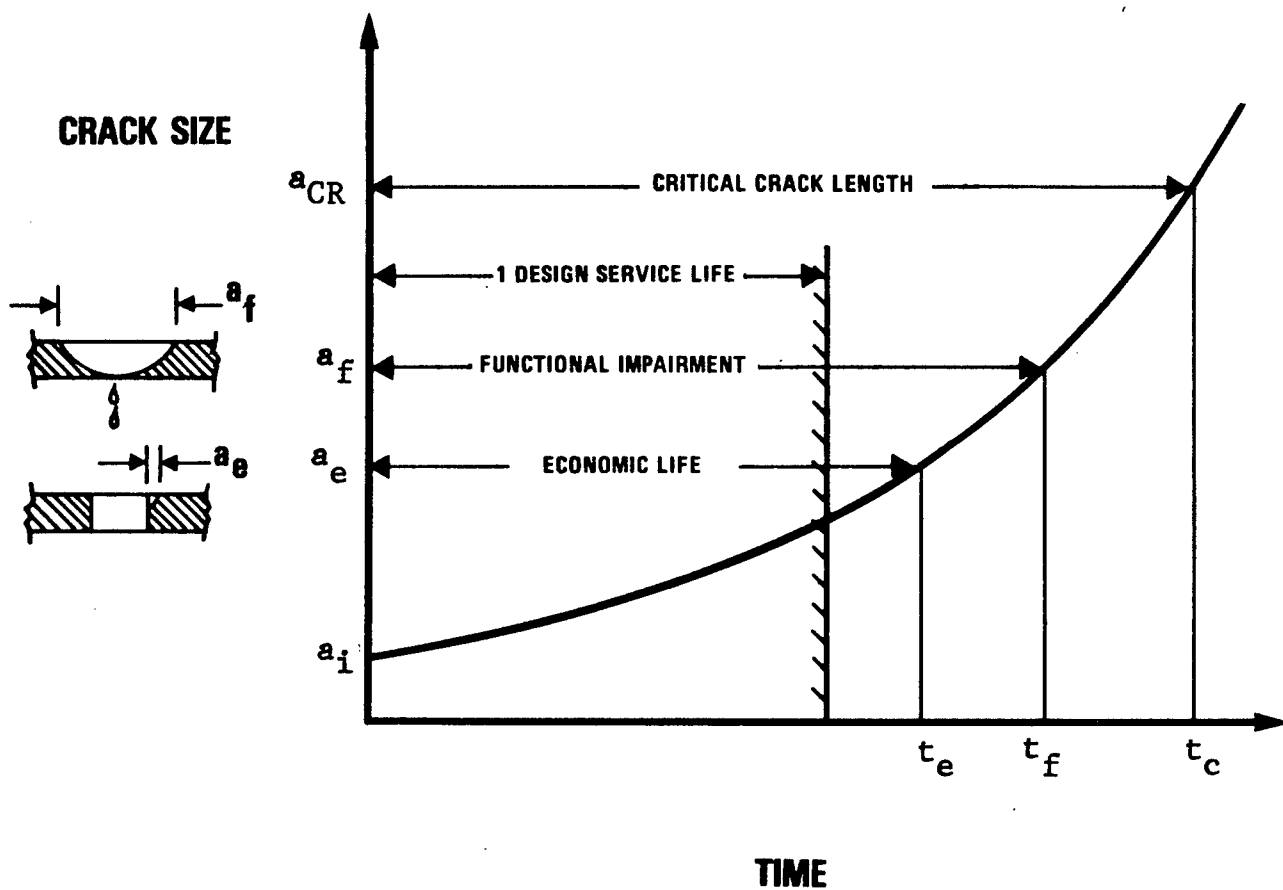


Figure 1 Conceptual Illustration of U. S. Air Force Durability Design Requirements

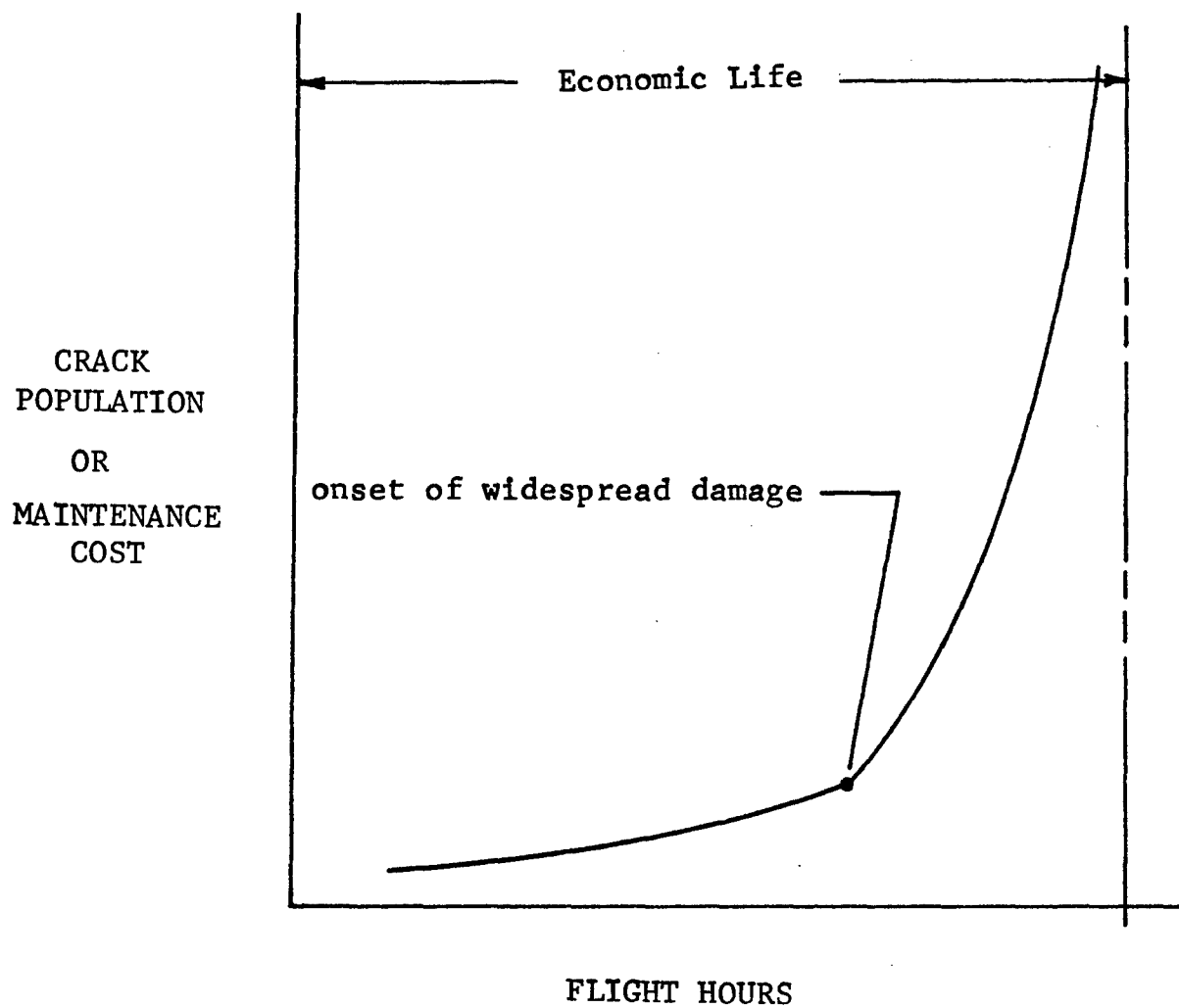


Figure 2 Widespread Damage Concept

components. These factors shall include initial quality and initial quality variations, environment, load sequence and environmental interactions effects, material property variation, and analytical uncertainties. The analysis shall demonstrate that cracks in the structure throughout one design lifetime shall not result in sustained crack growth under steady state flight (1G) and ground stress conditions. The design and analyses procedures shall be verified by test to selected design flight-by-flight stress and environment spectra and shall require approval by the procuring activity."

2.2.2 Experimental Requirements

Design development tests are required to provide an early evaluation of the durability of critical structural components and assemblies and an evaluation/verification of the durability analysis. A durability test for a full-scale airframe may also be required by the Air Force. The full-scale airframe durability test shall be scheduled such that one lifetime of durability testing plus an inspection of critical structural areas shall be completed prior to the full production go-ahead decision. Two lifetimes of durability testing plus an inspection of critical structural areas shall be scheduled to be completed prior to delivery of the first production airplane. If the economic life of the airframe is reached prior to two lifetimes of durability testing, sufficient inspection and data evaluation shall be completed prior to delivery of the first production airplane to estimate the extent of required production and retrofit changes. If the economic life of the airframe is not reached prior to two lifetimes of durability testing, a decision shall be made to (1) terminate the durability testing and perform a nondestructive inspection followed by a destructive teardown inspection, or (2) terminate the durability testing and perform damage tolerance testing and a nondestructive inspection followed by a destructive teardown inspection, or (3) continue the durability testing for an approved period of time followed by either (1) or (2). In-service nondestructive inspections shall also be performed at other intervals specified by the Air Force.

2.3 DURABILITY ANALYSIS ISSUES

The objective of this section is to review and discuss key issues affecting the durability analysis objectives and desired analytical format. This information will be used to establish an appropriate analytical format for the durability damage analysis methodology to be developed.

2.3.1 Durability Damage Modes

The durability damage analysis methodology to be developed under Phase I should be responsive to the most common type of durability damage encountered by in-service aircraft. A recent structural survey of aircraft at several Air Force Air Logistics Centers revealed that cracking is the most frequent structural degradation problem, followed by corrosion and fastener related problems [7]. Approximately 60% or more of the observed fatigue cracks originated at fastener holes [7]. Similar observations have been reported by Tiffany [4]. Accordingly, the durability damage analysis methodology to be developed should reflect cracking as the fundamental durability damage mode. Also, crack length will be used as the fundamental measure of durability damage. This damage measure is consistent with the Air Force damage tolerance philosophy [5].

2.3.2 Initial Quality

Initial quality is a quantitative "... measure of the condition of the airframe relative to flaws, defects, or other discrepancies in the basic materials or introduced during manufacture of the airframe" [2]. Initial quality is a random variable depending on several factors, including inherent material characteristics, material processing, handling, machining, fastener hole drilling procedures, assembly, etc. It provides a quantitative "benchmark" for the initial flaws in structural details (e.g., fastener holes) and the starting point for durability damage analyses.

Two methods for characterizing initial fatigue quality are: (1) the time-to-crack-initiation (TTCI) concept [8-10] and (2) the equivalent initial flaw size (EIFS) concept [11-24].

TTCI defines the time to initiate a specified observable crack size under specified design conditions in a structural detail (i.e., as manufactured with no initial flaws intentionally implanted). The longer the TTCI, the better the initial fatigue quality. TTCI's can be obtained using coupon specimens and full scale components.

An equivalent initial flaw size is a hypothetical crack assumed to exist in the structure prior to service. Such cracks do not necessarily have a direct physical relationship to actual initial flaws in the structure (e.g., size, geometry, location, number, etc.) Flaws observed during fatigue tests are extrapolated backward using a crack propagation law to estimate their "equivalent" initial flaw size (EIFS). Fractographic results are typically used to validate EIFS predictions. This approach implies that the entire fatigue process is essentially subcritical flaw growth.

Although TTCI values can be directly verified by actual observations, the resulting format is not suitable for direct crack growth analyses. On the other hand, the EIFS concept has a format directly applicable to crack growth analysis. Yet, the EIFS values cannot be directly verified using observed crack sizes. Both TTCI and EIFS concepts are useful for characterizing initial fatigue quality. These concepts should be considered in the durability damage analysis methodology to be developed under Phase I.

2.3.3 Economic Life

Economic life issues are discussed in this section to put them into proper perspective. This is essential to define durability analysis objectives and to develop a suitable analytical format.

The current definition of "economic life" and how it is used to implement the Air Force' durability design requirements is controversial. MIL-A-008866B [2] clearly states that an airframe must be designed to have an "economic life" greater than the design service life. Analytical assurance of airframe economic life is required [1,2] and it must be verified experimentally [3].

Economic life is currently defined in vague terms such as (1) "...occurrence of widespread damage which is uneconomical to repair..." [2] and (2) "...that point in time when it is more economical to replace than to repair" [4]. A fixed criterion for economic life is not available for analytically assuring airframe durability during the design stage. As a result, designers are forced to use whatever analytical tools they have to show their design is "durable". Then they have to wait until the durability verification test is performed to determine if the airframe satisfies the "economic life" requirements.

Currently, airframe economic life is based on the results of the full-scale durability test article and results of the tear-down inspection. Even then, the definition of economic life is subjective with no standard criterion for contractual compliance.

Several questions must be answered before an economic life standard for compliance can be developed: (1) What is widespread damage?, (2) What are acceptable limits for structural maintenance costs before replacement?, (3) How much downtime is intolerable for structural maintenance/operational readiness considerations?, and (4) How long is an aircraft's technology viable before retirement? MIL-A-008866B states that "...the economic life must exceed the design service life...". At what service life should economic life be defined (e.g., 1.2 SL?, 1.5 SL?)? The aircraft user must answer these questions because only he can define what he is willing to tolerate in service.

The Air Force MIL specifications [1-3] refer to economic life in terms of the airframe. Airframe durability is considered to be governed by the quantitative damage incurred by structural details (e.g., fastener holes), by parts or by components comprising the airframe and the combined effects of the damage on the user's structural maintenance costs and operational readiness.

Based on the above, the durability analysis methodology to be developed under Phase I should provide the analytical tools for quantifying durability damage (e.g., how many details have a crack size greater than a specified size?). The quantitative definition of economic life requires further study and evaluation, but this is beyond the scope of this program. Developing the tools for analytically quantifying durability damage is the first requisite step for developing methodology for assuring airframe durability.

2.3.4 Economic Limit

The economic (repair) limit has been defined as "...the most opportune time for economic repair or modification of the structure (e.g., the time when fastener hole oversizing should be accomplished) ..." [4]. The economic repair limit for a fastener hole is reached when the largest radial crack in the hole reaches a size that can still be cleaned up by reaming the hole to the next fastener size (e.g., 0.030" - 0.050"). Since fatigue cracks frequently originate at fastener holes, this philosophy could be useful for defining durability damage limits during the design stage.

Fatigue cracks are also likely to originate at cutouts, radii and other structural discontinuities. However, there is no well defined criterion for the economic repair limit for such details.

2.3.5 Durability Design Tradeoffs

The durability damage analysis methodology should be useful for evaluating design tradeoffs and for analytically quantifying user options affecting operating costs, care and use of the aircraft. Analytical tools are needed for quantifying the effects of design variables, such as, material, allowable stress level, initial quality, manufacturing procedures, loading spectra, maintenance requirements, etc., on the "durability" of the aircraft structure under design service conditions. By quantifying Air Force durability options during the design stage, the user can more actively participate in making airframe design decisions affecting aircraft operating costs, performance, and operational readiness.

2.4 DURABILITY DAMAGE ANALYSIS OBJECTIVES

Objectives of the durability damage analysis methodology to be developed are:

1. Analytically assure airframe durability during the design stage for different materials, stress levels, design spectra, manufacturing variables, etc.

2. Evaluate durability design tradeoffs and Air Force options affecting life-cycle-costs and operational readiness.
3. Support durability verification test plan and evaluation.
4. Define initial structural maintenance policy before aircraft is committed to service.

2.5 ANALYTICAL FORMAT FOR DURABILITY DAMAGE ANALYSIS

The recommended analytical format for quantifying durability damage is conceptually described in Fig. 3. A similar flaw growth model has been proposed [12]. Essential elements of the analytical format are:

1. Crack length is the fundamental measure of durability damage.
2. Initial fatigue quality is a random variable characterized in terms of crack length and/or time-to-crack initiation.
3. The distribution (or population) of crack sizes for a group of structural details (e.g., fastener holes) is composed of the dominant crack (i.e., the largest) in each detail. The objective is to predict the growth of the entire population of dominant cracks as a function of service hours using applicable design variables and loading spectra.
4. Durability damage is given by the number of structural details exceeding a specified crack size after a specified service period.
5. A statistical format is used for quantifying confidence bounds for damage predictions.

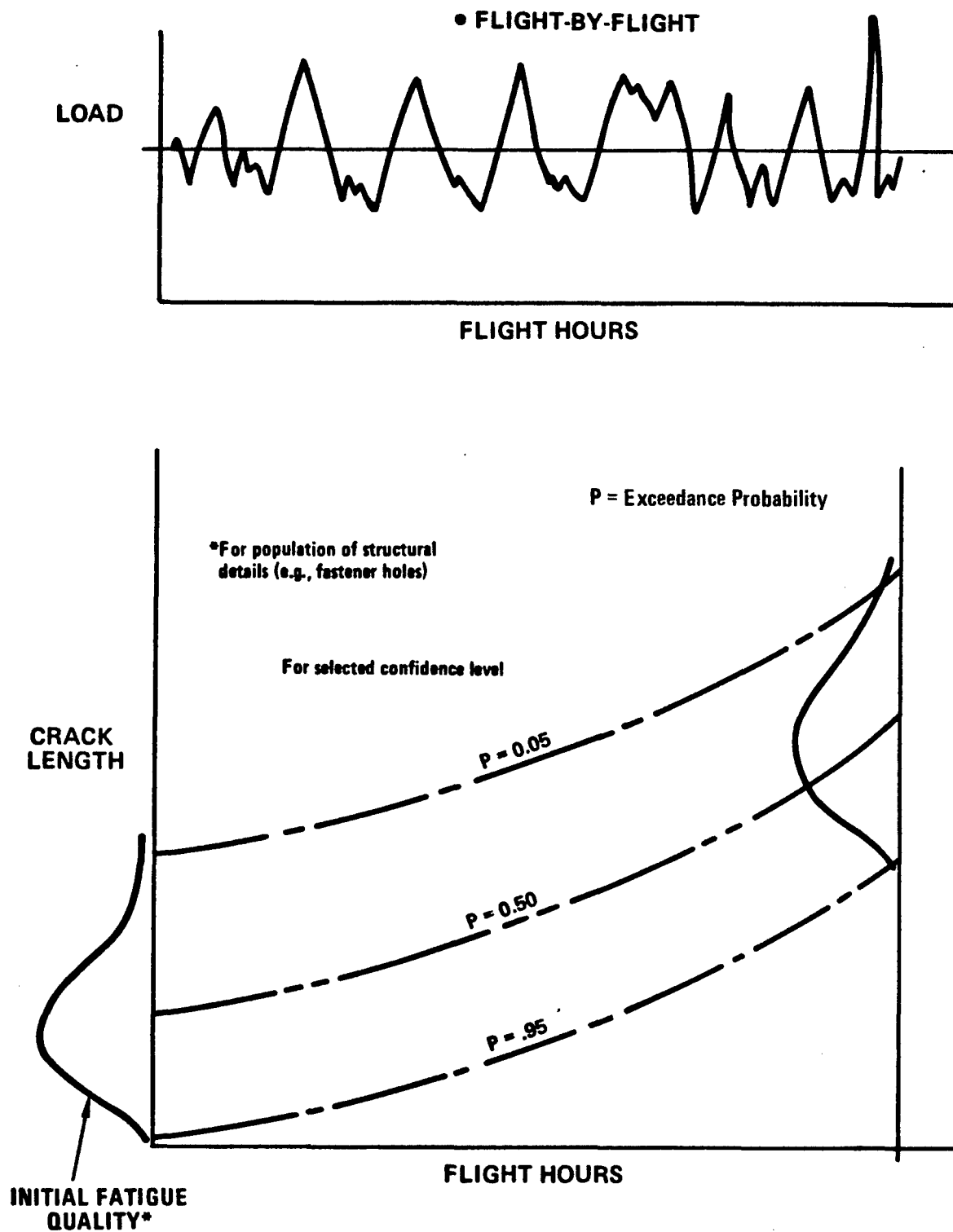


Fig. 3 Analytical Format for Durability Analysis

S E C T I O N I I I

CRITICAL EVALUATION OF APPROACHES FOR DURABILITY DAMAGE ANALYSIS

3.1 INTRODUCTION

The objective of Section III is to determine the most promising analytical approach and concepts for developing the durability analysis methodology under Phase I. Existing analytical approaches with potential for durability analysis are cataloged into three groups for evaluation purposes. Each "approach" is considered in terms of its underlying analytical philosophy and concepts rather than specific detailed procedures as such. Also, some approaches were not developed to quantify durability damage in the first place because of their inapplicability for durability.

The applicability and potential of existing approaches for durability analysis applications is evaluated. Each approach is considered in the context and present stage of development. The applicability and potential of the underlying concepts for satisfying the durability analysis format developed in Section II is emphasized.

3.2 CATALOGING ANALYTICAL APPROACHES

An extensive literature survey has been performed to identify existing analytical approaches and/or concepts with possible potential for durability damage analysis applications [25]. Existing approaches were screened and then cataloged, into three groups:

1. Conventional Fatigue Analysis (Palmgren-Miner Rule) (CFA). [26,27]
2. Deterministic Crack Growth Approach (DCGA) [e.g., 12, 28-31].
3. Probabilistic Crack Growth Approach (PCGA) [14,16, 20,23,24].

Approaches were cataloged on the basis of underlying analytical philosophy. Some approaches include concepts applicable to one or more of the three groups. For example, statistical and probabilistic concepts can be applied to any of the three groups.

Three general methods were cataloged under CFA: (1) linear cumulative damage [26,27,32], (2) non-linear cumulative damage [33,34] and (3) local strain method [e.g., 35-37]. Although these methods may differ in specific details, they are generally concerned with a cumulative damage type analysis. The CFA described and evaluated in this section will be limited to the Palmgren-Miner rule.

Both the DCGA and the PCGA are crack growth oriented. Whereas the DCGA predicts the growth of a single crack, the PCGA recognizes the growth of a population of cracks. In this report, the PCGA is described by References 14,16,20,23 and 24.

3.3 CONCEPTUAL DESCRIPTION

The main purpose of this section is to describe the underlying philosophy of each analytical approach rather than detailed procedures. Each analytical approach will be conceptually described to evaluate their applicability and usefulness for satisfying: (1) durability analysis objectives and (2) analytical format for quantifying the extent of durability damage. The three approaches are conceptually described in terms of crack size versus time in Fig. 4.

3.3.1 Conventional Fatigue Analysis (CFA)

According to the Palmgren-Miner cumulative damage rule, fatigue damage is linearly accumulated; when the total accumulated damage ratio, $\sum_{i=1}^m \frac{n_i}{N_i}$, equals 1, fatigue failure is

assumed to occur. n_i is the number of cycles applied at a corresponding stress amplitude, N_i is the number of cycles to failure at the corresponding stress amplitude, and m is the number of equivalent cycle segments for damage accumulation.

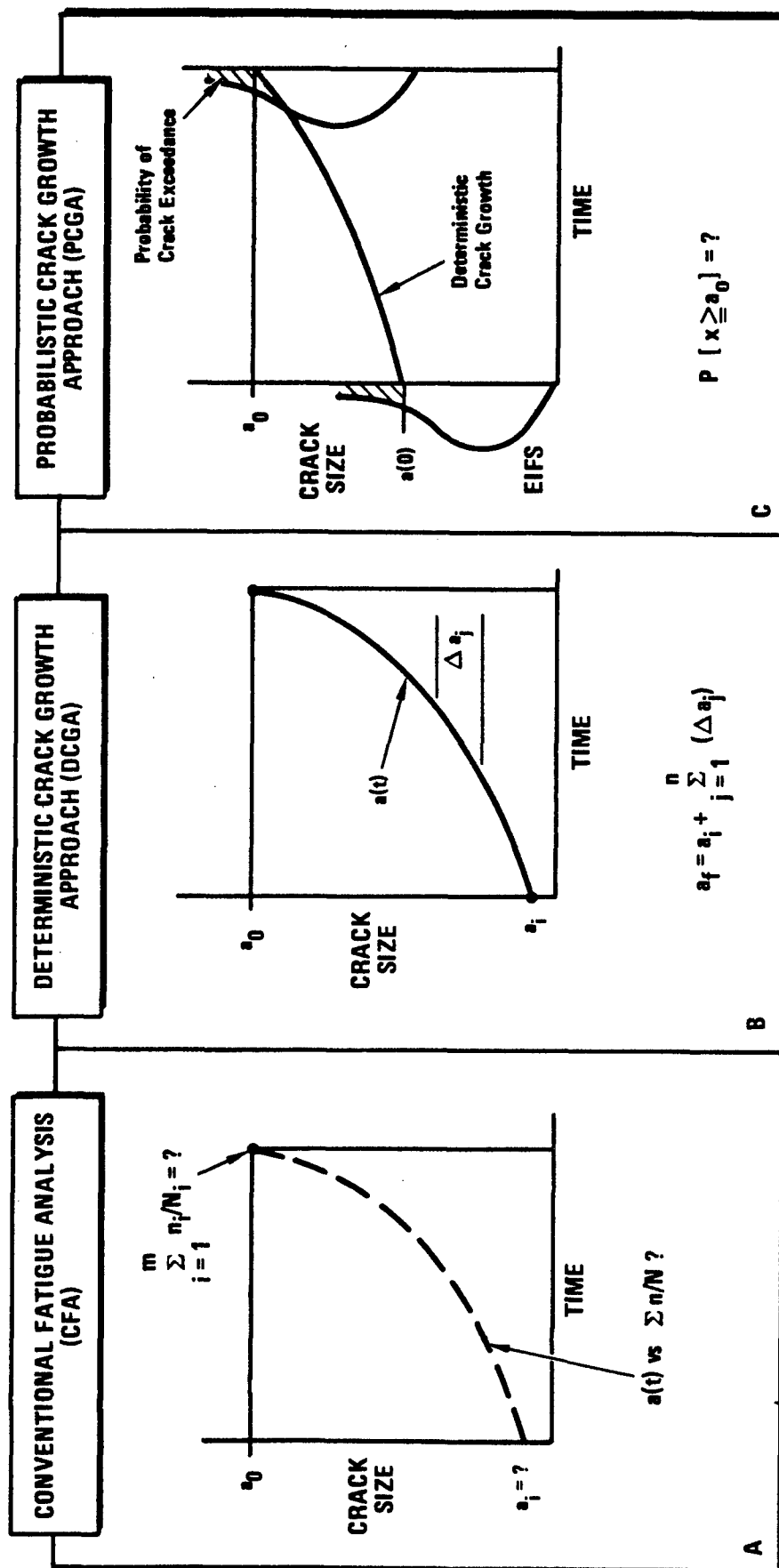


Fig. 4 Conceptual Comparison of Three Possible Durability Analysis Approaches In A Crack Growth Format

Basic assumptions used for this approach are:

- (1) The fatigue damage produced in the material by one stress level does not affect the damage produced by another stress level. Thus, fatigue damage is independent of the loading sequences; fatigue damage growth retardation and acceleration effects are not considered.
- (2) Fatigue damage incurred during one loading cycle is linearly accumulated to one produced during the pre-historical loading.
- (3) The simplified cycle counting scheme for spectrum loading simulates the actual service spectrum with reasonable accuracy.
- (4) S-N curves from the adequately designed notched specimens reflect the applicable material, notch (or crack) intensity factor due to the geometry of control point, service environment and loading condition, etc.

Details of the Palmgren-Miner rule are described elsewhere [26,27].

3.3.2 Deterministic Crack Growth Approach (DCGA)

Cracks are assumed to be randomly produced in aircraft structure during material processing, handling, manufacturing, assembly, etc. Since cracks are assumed to exist in the structure prior to service, structural life is dominated entirely by crack growth.

The DCGA accounts for several design variables, such as, material properties, different materials, stress levels, loading spectra, initial fatigue quality, and environment. The basic objective of the method is to predict the growth of a given initial flaw size under design conditions. As such, it is usually concerned with the growth of a single dominant crack at a given location, geometry, material, design concept and maximum stress level. For damage tolerance analysis, a worst-case crack size is assumed initially present at the most critical structural location. The ultimate design goal in this case is to assure that the crack will not reach catastrophic proportions during the service life of the aircraft structure.

Basic elements of the DCGA are:

- o initial flaw size and geometry for starting the analysis
- o stress intensity factor at the tip of a crack
- o cycle counting scheme for interpreting spectrum loading in terms of "equivalent" constant amplitude cycles
- o da/dn versus ΔK data for constant amplitude testing
- o load interaction retardation and acceleration models
- o crack growth accumulation scheme, i.e.,

$$a_f = a_i + \sum_{j=1}^n (\Delta a_j) \quad (1)$$

where: a_f = accumulated crack length

a_i = initial crack size

Δa_j = crack growth increment for jth interval

Reference Fig. 4, Frame B for conceptual description.

The DCGA treats random variables as fixed values in the analysis. For each set of input parameters there is a single value prediction for the crack size. Thus, a new prediction is obtained for each set of input parameters. This process is called deterministic because random variables are treated as discrete values in the analysis.

3.3.3 Probabilistic Crack Growth Approach (PCGA)

The PCGA, within the scope of this report, is described in References 14, 16, 20, 23 and 24. This approach seeks to quantify the growth of a population of cracks as a function of service hours (Fig. 4, Frame C).

Initial fatigue quality is based on the integration of two concepts: time-to-crack-initiation (TTCI) [8-10] and

equivalent initial flaw size (EIFS) [11-24]. The TICI, described by a three-parameter distribution, and a deterministic crack growth law are used to derive the EIFS distribution [23, 24]. A conceptual description of the initial fatigue quality model is shown in Fig. 5.

Structural damage is quantified by the length of the dominant fatigue crack emanating from each structural detail (e.g., fastener hole, fillet, cutout, etc.). Each fastener hole, for example, is a member of the total population of fastener holes in a part, component or assembly. Fatigue crack size is considered to be a random variable as a function of time.

The PCGA accounts for initial fatigue quality, crack growth accumulation in a population of details, load spectrum and material/structural properties.

Crack sizes at a given time are cast in a probabilistic format. For example, crack sizes are treated as a statistical distribution or population of values with a mean and variance. The distribution of crack sizes are transformed from one time to another by deterministic crack growth. Unlike the DCGA, the entire population of cracks is grown as a function of time rather than a single crack.

The extent of structural damage at a given time can be quantified in terms of the probability of crack exceedance. This quantity simply represents the portion of the total crack population which equals or exceeds a specified damage (crack) size. The dominant crack in a structural detail is assumed to be relatively small (e.g., ≤ 0.030 " to 0.050 " radial crack in fastener hole). Such cracks are assumed to be statistically independent. Thus, the extent of structural damage can be quantified for a detail or group of details using binomial statistics [e.g., 38] and the confidence level in the prediction can be judged.

3.4 CRITICAL EVALUATION OF APPROACHES

Each of the three approaches (i.e., CFA, DCGA and PCGA) are evaluated to determine their applicability and/or usefulness for analytically assuring airframe durability during the design stage. The three approaches are conceptually described

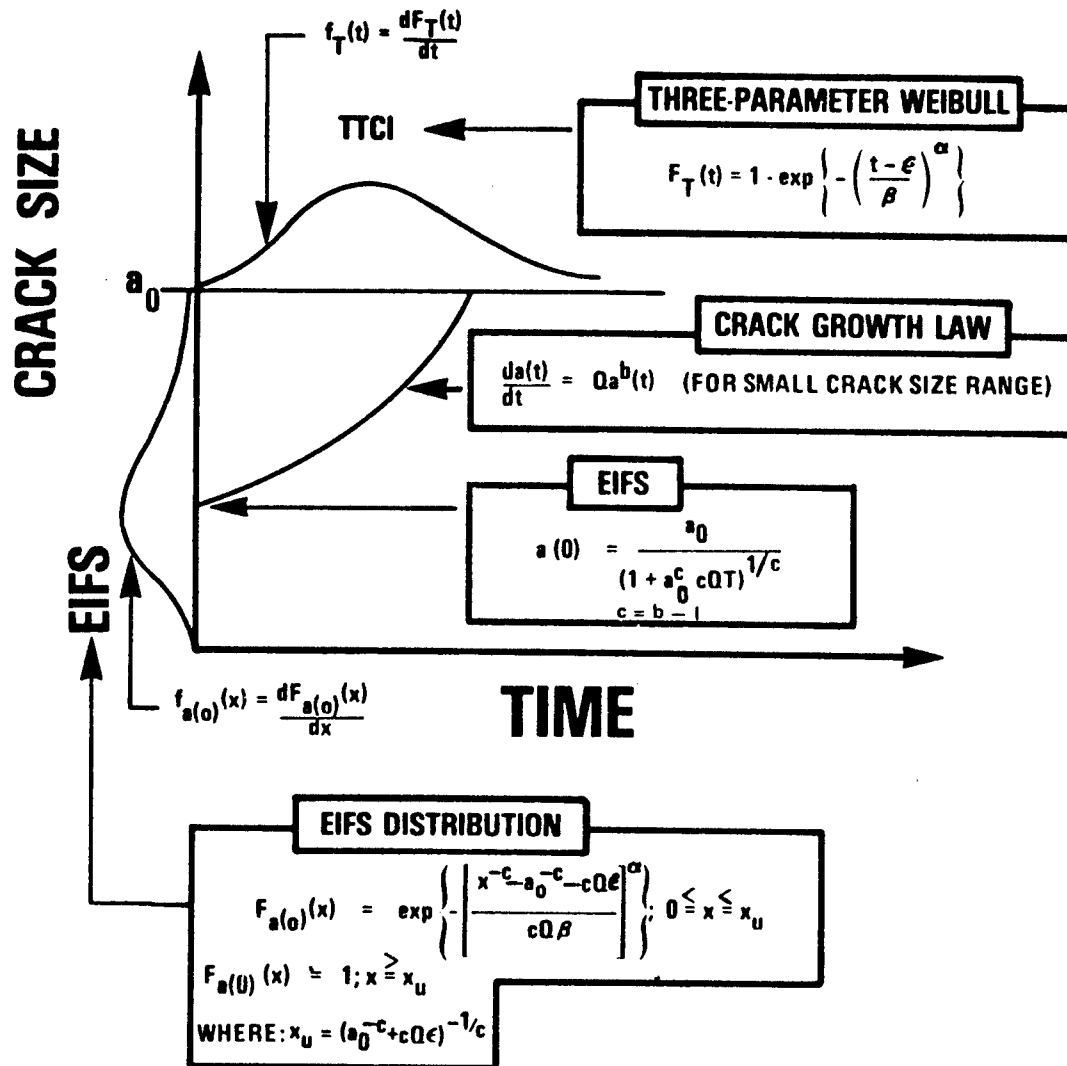


Figure 5 Elements of Initial Fatigue Quality Model

in a crack growth format for comparison and evaluation purposes in Fig. 4. In Table 1, these are compared in terms of specific durability analysis formats. Details of the evaluation are described and discussed below.

3.4.1 Conventional Fatigue Analysis (CFA)

In general, CFA does not assume pre-existing initial flaws. Therefore, fracture mechanics concepts for crack size determination cannot be properly accounted for in this approach. This approach does not recognize the crack size as a function of time which is essential for durability damage analysis. Since this approach implicitly includes the crack initiation life as well, it may be possible to calibrate the S-N data for a specified crack initiation size. However, in any case, simple CFA does not satisfy the analytical format required to quantify durability damage for multiple flaws and structural details (Table 1).

Although CFA is incapable of quantifying durability damage, it is still useful for preliminary durability design as follows: (1) screen materials and design configurations, (2) set preliminary design allowables, (3) identify potential fatigue "hot spots", (4) make design tradeoff studies and (5) quantitatively evaluate effects of load spectra variations. CFA is useful as a preliminary durability design tool.

3.4.2 Deterministic Crack Growth Approach (DCGA)

The DCGA is fracture mechanics oriented and can be used to analytically quantify durability damage for a single crack and a given detail. Initial fatigue quality can be accounted for using this approach. However, only one initial crack size can be used at a time in the analysis. Therefore, the DCGA does not have the proper analytical framework for directly predicting the durability damage distribution for multiple structural details as a function of time.

The DCGA can be used to quantify durability damage by grouping details (e.g., fastener holes) for similar stress levels and stress histories. The "durability" for a group of details is determined based on the time for the most critical detail in the group to reach a specified crack size (Fig. 4). This approach for quantifying damage is generally conservative for assuring durability because the prediction is based on

Table 1 Comparison of Approaches In Terms of Durability Analysis Format

APPROACH DURABILITY ANALYSIS FORMAT FOR	CFA	DCGA	PCGA
FUNDAMENTAL DURABILITY DAMAGE MEASURE	DAMAGE RATIO: $\frac{n}{N}$ (Not Crack Length)	CRACK LENGTH	CRACK LENGTH
INITIAL FATIGUE QUALITY VARIATION	CONSIDERED ONLY INDIRECTLY VIA S-N RESULTS	SINGLE VALUE FOR INITIAL CRACK SIZE	DISTRIBUTION OF INITIAL CRACK SIZES
CRACK GROWTH FOR MULTIPLE DETAILS	NOT CONSIDERED	SINGLE CRACK FOR SINGLE DETAIL	POPULATION OF CRACKS FOR GROUP OF DETAILS
QUANTITATIVE DESCRIPTION OF DURABILITY DAMAGE AS FUNCTION OF TIME	$D = \sum_{i=1}^m \frac{n_i}{N_i}$	SINGLE CRACK SIZE PREDICTION FOR A GIVEN TIME	NO. OF DETAILS WITH A DOMINANT CRACK \geq SPECIFIED SIZE AT A GIVEN TIME
QUANTIFYING CONFIDENCE LIMITS FOR DAMAGE PREDICTION	CAN BE DEFINED USING STATISTICAL METHODS BY CASTING RESULTS IN A STATISTICAL FRAMEWORK		STATISTICAL FRAMEWORK FOR DIRECTLY ASSESSING CONFIDENCE LIMITS.

the time for the most critical detail in the group to reach a specified crack size (Fig. 4). This approach for quantifying damage is generally conservative for assuring durability because the prediction is based on "worst case" values and does not recognize the distribution of flaws as a function of time. The distribution of crack sizes for multiple details could be determined using Monte Carlo simulations [39] but this is considered to be inefficient and time consuming.

DCGA is also useful for screening material, setting preliminary design stress levels, identifying fatigue "hot spots", evaluating design tradeoffs, evaluating results from the durability verification test, etc. However, two shortcomings of the DCGA for durability applications are: (1) it does not treat initial quality as a random variable and (2) it is basically a single-value prediction method -- therefore, it cannot effectively predict the crack growth for a distribution of crack sizes for multiple structural details.

3.4.3 Probabilistic Crack Growth Approach (PCGA)

The PCGA is very promising for developing the "Durability Analysis Methodology" under Phase I. As shown in Table 1, the PCGA satisfies the durability analysis format developed in Section II. This approach can account for the initial fatigue quality variation, different materials, variation of material properties, different stress levels and loading spectra, etc. The PCGA not only provides a meaningful format for quantifying durability damage and the extent of damage, but also the means for estimating confidence limits for the prediction.

The probability of crack exceedance is a useful concept for describing the extent of structural damage. It is also promising for developing quantitative criteria for economic life.

Describing the distribution of crack sizes as a function of time is a convenient format for evaluating and visualizing structural degradation. The PCGA uses probabilistic, statistical, and deterministic principles. Since these concepts are relatively simple, only an elementary understanding of probability and statistics is required to implement the PCGA.

By using Binomial statistics [e.g., 23], the extent of durability damage for individual details or components can be combined into an overall prediction. This allows estimates to be made for the extent of structural damage during the design stage -- before aircraft structure is committed to production or service. Thus, durability design tradeoffs affecting economic life, operational readiness and structural maintenance requirements can be evaluated at a critical stage of design development.

S E C T I O N I V

CONCLUSIONS

The PCGA is the most promising of the three approaches considered for durability analysis applications. It provides a suitable analytical framework for satisfying the Air Force's durability design requirements. The PCGA can be used to predict the extent of structural damage (e.g., the probable number of fastener holes exceeding a specified crack size) for multiple structural details. Since a statistical framework is used, the confidence level for the prediction can be determined. Thus, the PCGA provides the type of information needed to judge economic life.

Several PCGA concepts, promising for durability analysis, are depicted in Figure 6. These concepts should be considered in the "Durability Analysis Methodology" to be developed in Phase I.

Neither the CFA nor the DCGA have the proper format for analytically assuring the Air Force's durability design requirements. CFA (i.e., Palmgren-Miner rule) is incapable, in its present form, of quantifying the extent of structural damage in meaningful terms for judging economic life. The DCGA can be used to predict the growth of a single crack as a function of time. But, it is incapable of directly predicting the overall crack growth behavior of the population of cracks in multiple structural details (e.g., fastener holes).

Quantitative economic life criteria remain to be developed. However, given the criterion for economic life, the extent of structural damage prediction can be used to analytically assure design compliance.

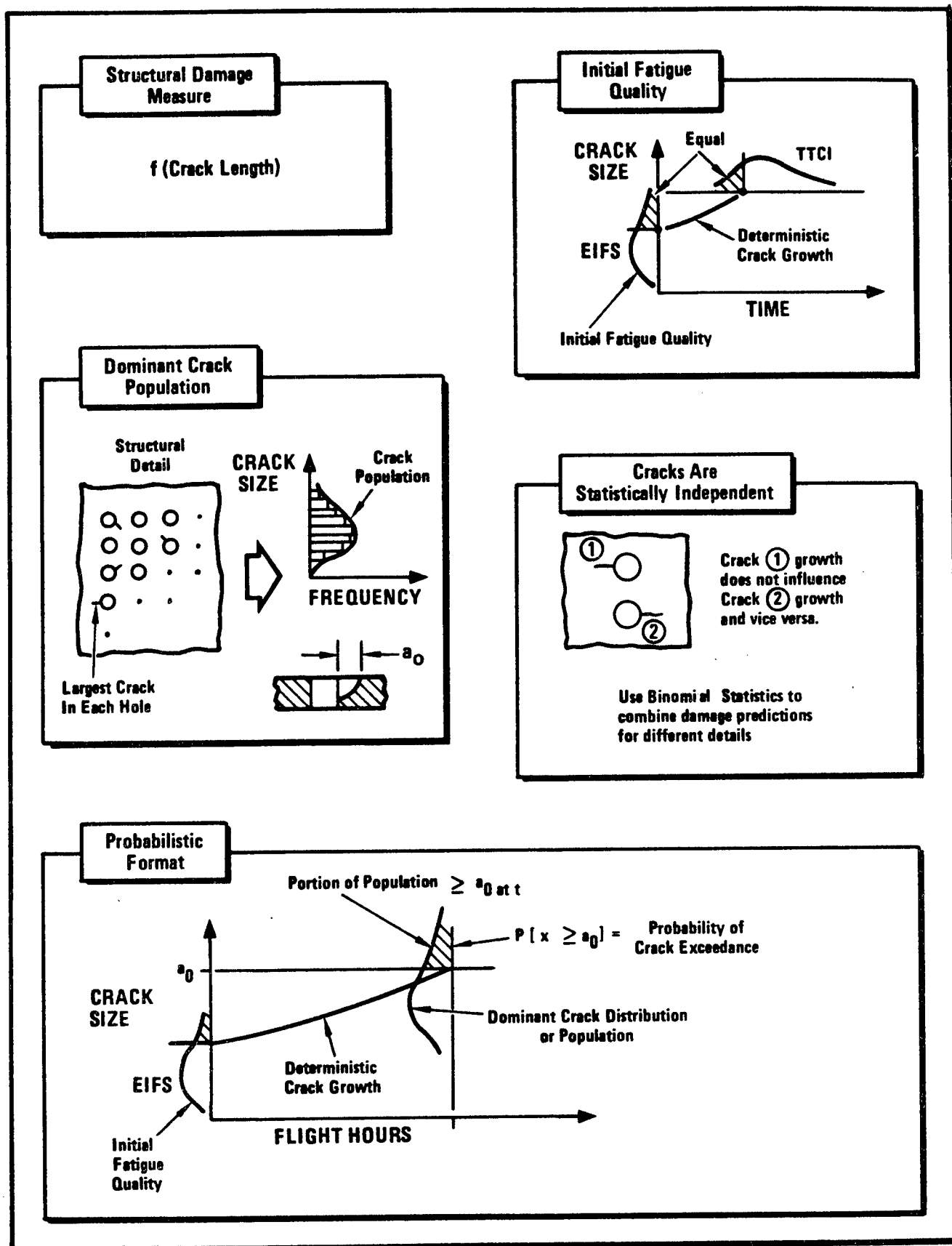
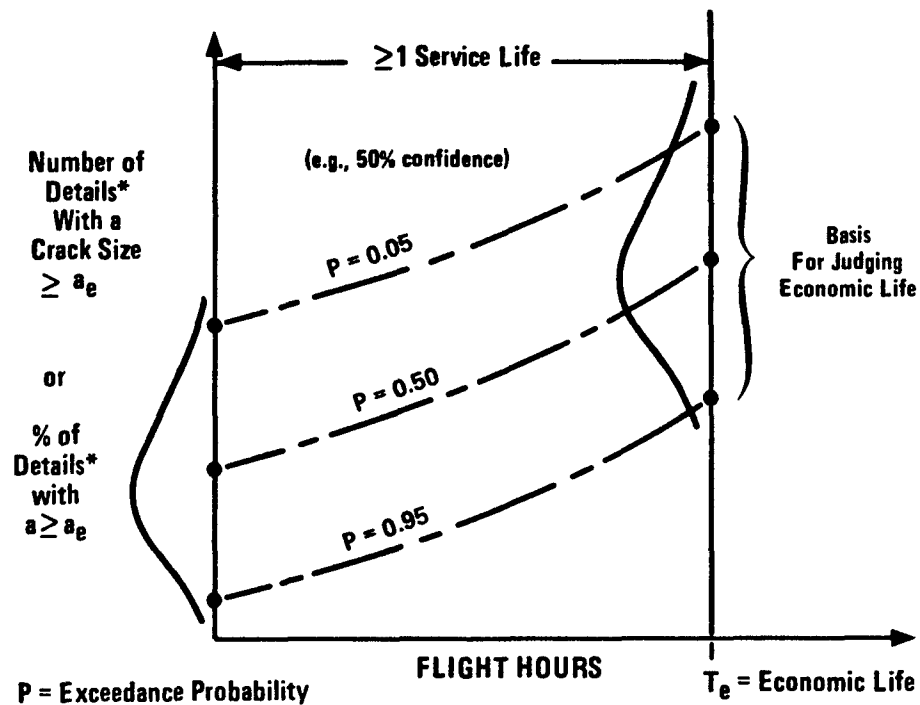


Fig.6 Useful PCGA Concepts For Durability Analysis Methodology Development

**Extent of Durability Damage
and Confidence Level**

• PROBABILITY OF CRACK EXCEEDANCE



*e.g. Fastener Holes

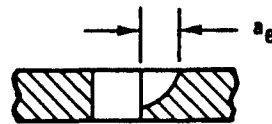


Fig. 6 (Continued)

REFERENCES

1. MIL-STD-1530A(11), "Aircraft Structural Integrity Program", 11 December 1975.
2. MIL-A-8866B (USAF), "Airplane Strength and Rigidity Reliability Requirements, Repeated Loads and Fatigue", 22 August 1975.
3. MIL-A-8867B (USAF), "Airplane Structural Ground Tests", January 1975.
4. C. F. Tiffany, "Durability and Damage Tolerance Assessments of United States Air Force Aircraft," Paper Presented at AIAA Structural Durability and Damage Tolerance Workshop, Washington, D.C., April 6-7, 1978.
5. MIL-A-83444 (USAF), "Airplane Damage Tolerance Requirements", July 1974.
6. "A Technical Proposal for Durability Methods Development" Presented to AFFDL In Response to Solicitation No. F33615-77-R-3123, General Dynamics, Fort Worth Division, Report FZP-1865, 18 July 1977.
7. B. J. Pendley, S. P. Henslee and S. D. Manning, "Durability Methods Development, Volume III - Structural Durability Survey: State-of-the-Art Assessment," AFFDL-TR-79-3118, September 1979.
8. A. M. Freudenthal, "The Expected Time to First Failure," Air Force Materials Laboratory, AFML-TR-66-37, February 1966.
9. A. M. Freudenthal, H. Itagahi, and M. Shinozuka, "Time to First Failure for Various Distributions of Time to Failure", Air Force Materials Laboratory, AFML-TR-66-241, July 1966.
10. J. N. Yang and W. J. Trapp, "Joint Aircraft Loading/Structure Response Statistics to Time to Service Crack Initiation", AFML-TR-74-174, November 1974.
11. T. D. Gray, "An Equivalent Initial Flaw Analysis of the A-7A Wing Fatigue Test", LTV Aerospace Corporation, Report No. 2-53410/ASIP/5DIR-10, May 1975.

12. H. A. Wood, R. M. Engle, J. P. Gallagher, J. M. Potter, "Current Practice on Estimating Crack Growth Damage Accumulation with Specific Application to Structural Safety Durability and Reliability", Air Force Flight Dynamics Laboratory, AFFDL-TR-75-32, January 1976.
13. J. L. Rudd and T. D. Gray, "Equivalent Initial Quality Method", U. S. Air Force Flight Dynamics Laboratory, AFFDL-TM-76-83, 1976.
14. J. N. Yang, "Statistical Estimation of Service Cracks and Maintenance Costs for Aircraft Structures", Journal of Aircraft, AIAA, Vol. 13, No. 12, 1976, pp. 920-937.
15. R. E. Pinckert, "Damage Tolerance Assessment of F-4 Aircraft:", Paper presented at the AIAA Aircraft Systems and Technology Meeting, Dallas, Texas, September 27-29, 1976.
16. W. S. Johnson, R. A. Heller and J. N. Yang, "Flight Inspection Data, Crack Initiation Times, and Initial Crack Size", Proceedings 1977 Annual Reliability and Maintainability Symposium, January, 1977, pp. 148-154.
17. J. L. Rudd, "Applications of the Equivalent Initial Quality Method", U. S. Air Force Flight Dynamics Laboratory, Technical Memorandum, AFFDL-TM-77-58-FBE, July 1977.
18. J. L. Rudd and T. D. Gray, "Quantification of Fastener Hole Quality", Journal of Aircraft, Vol. 15, No. 3, March 1978, pp. 143-147.
19. "Analysis of USAF Aircraft Structural Durability and Damage Tolerance", Workshop Notebook, Washington, D.C., April 6-7, 1978.
20. J. N. Yang, "Statistical Approach to Fatigue and Fracture Including Maintenance Procedures", Paper presented at the Tenth Symposium on Naval Structural Mechanics, Washington, D.C., September 1978. Reference Fracture Mechanics, University Press of Virginia, Charlottesville, 1978, pp. 559-577.
21. J. M. Potter, "Advances in Fastener Hole Quality Through the Application of Solid Mechanics", Paper presented at Army Symposium on Solid Mechanics, 1978 Case Studies on Structural Integrity and Reliability, Cape Cod, Mass. October 3-5, 1978.

22. P. J. Noronha, et al., "Fastener Hole Quality", Report AFFDL-TR-78-206, Vol. I, December 1978.
23. J. N. Yang, "Statistical Estimation of Economic Life for Aircraft Structures", Proc. AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference, April 4-6, 1979, St. Louis, pp. 240-248.
24. J. N. Yang and S. D. Manning, "Distribution of Equivalent Initial Flaw Size", 1980 Proceedings Annual Reliability and Maintainability Symposium, San Francisco, CA, 22-24 Jan. 1980, pp. 112-120.
25. S. D. Manning, W. R. Garver and Y. H. Kim, "Durability Methods Development, Volume II - Durability Analysis: State-of-the-Art Assessment", General Dynamics, Fort Worth Division Report FZM-657-II, June, 1979.
26. A. Palmgren, "Die Lebensdauer Von Kugellagren, "Zeitschrift des Vercines Deutschor Ingenienro, Vol. 68, No. 14, April 5, 1924, pp. 339-341.
27. M. A. Miner, "Cumulative Damage in Fatigue", Journal of Applied Mechanics, ASME J. of Applied Mechanics, Vol. 12, No. 3, September 1945, pp. A-159-A-164.
28. R. E. Pinckert, "Damage Tolerance Assessment of F-4 Aircraft", Paper presented at the AIAA Aircraft Systems and Technology Meeting, Dallas, Texas, September 27-29, 1976.
29. "Analysis of USAF Aircraft Structural Durability and Damage Tolerance", Workshop Notebook, Washington, D.C., April 6-7, 1978.
30. H. A. Wood, "The Use of Fracture Mechanics Principles in the Design and Analyses of Damage Tolerant Aircraft Structures AGARD-LS-62, May 1973.

31. S. D. Manning and J. M. Norton, "Deterministic and Probabilistic Fracture Mechanics", 1978 ASQC Technical Conference Transactions - Chicago, pp. 245-254.
32. H. J. Grover, "Cumulative Damage Theories," Proceedings of the Symposium on Fatigue of Aircraft Structures, WADC Technical Report 59-57, Aug. 1959, pp. 207-225.
33. D. L. Henry, "A Theory of Fatigue - Damage Accumulation In Steel," ASME Transactions, Vol. 77, No. 6, August 1955, pp. 913-918.
34. H. T. Corton and T. J. Dolan, "Cumulative Fatigue Damage," Proceedings of International Conference on Fatigue of Metals, British Institute of Mechanical Engineers London, 10-14 Sept. 1956.
35. M. R. Mitchell, "Fundamentals of Modern Fatigue Analysis for Design", Paper presented at the 1978 ASM Materials Science Seminar, 14-15 October 1978, St. Louis, Missouri, Fatigue and Microstructure, American Society for Metals, Metals Park, Ohio, 1979, pp. 385-437.
36. N. E. Dowling, W. R. Brose and W. K. Wilson, "Notched Member Fatigue Life Predictions By the Local Strain Approach," Fatigue Under Complex Loading: Analyses and Experiments. Warrendale, PA: The Society of Automotive Engineer, Inc., 1977, pp. 55-84.
37. H. O. Funchs, "Discussion: Nominal Stress or Local Strain Approaches to Cumulative Damage," Fatigue Under Complex Loading: Analyses and Experiments. Warrendale, PA: The Society of Automotive Engineers, Inc. 1977, pp. 203-207.
38. L. Mann, Jr., Applied Engineering Statistics for Practicing Engineers, Barnes & Noble, Inc., 1970, pp. 26-30.
39. J. R. Benjamin and C. A. Cornell, Probability, Statistics and Decisions for Civil Engineers, McGraw-Hill Book Co., New York, 1970, pp. 124-133.